

Is *macroturbulent* broadening in OB Supergiants related to pulsations? *

S. Simón-Díaz^{1,2,**}, K. Uytterhoeven³, A. Herrero^{1,2}, N. Castro^{1,2}, J. Puls⁴ and C. Aerts^{5,6}

¹ Instituto de Astrofísica de Canarias, E38200 La Laguna, Tenerife, Spain.

² Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain.

³ Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot; CEA, IRFU, SAp, centre de Saclay, 91191, Gif-sur-Yvette, France.

⁴ Universitätssternwarte München, Scheinerstr. 1, 81679 München, Germany

⁵ Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium

⁶ IMAPP, Department of Astrophysics, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, the Netherlands

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The spectrum of O and B Supergiants is known to be affected by an important extra line-broadening (usually called *macroturbulence*) that adds to stellar rotation. Recent analysis of high resolution spectra has shown that the interpretation of this line-broadening as a consequence of large-scale turbulent motions would imply highly super-sonic velocity fields, making this scenario quite improbable. Stellar oscillations have been proposed as a likely alternative explanation. We present first encouraging results of an observational project aimed at investigating the *macroturbulent* broadening in O and B Supergiants, and its possible connection with spectroscopic variability phenomena and stellar oscillations: a) all the studied B Supergiants show line profile variations, quantified by means of the first ($\langle v \rangle$) and third velocity ($\langle v^3 \rangle$) moments of the lines, b) there is a strong correlation between the peak-to-peak amplitudes of the $\langle v \rangle$ and $\langle v^3 \rangle$ variability and the size of the extra-broadening.

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1 Introduction

The presence of an important extra line-broadening (in addition to the rotational broadening, and usually called *macroturbulence*) affecting the spectra of O and B Supergiants (Sgs) has been confirmed by several authors since the first studies of line-broadening in O and B stars early in the 1950's. It was initially suggested by the deficit of narrow lined objects among these type of stars (Slettebak 1956; Conti & Ebbets 1977; Howarth et al. 1997). The advent of high-quality spectra allowed to confirm that the rotational broadening alone was not sufficient to fit the line profiles in many objects, and to investigate the possible disentangling of both broadening contributions (see e.g. Ryans et al. 2002; Simón-Díaz & Herrero 2007). These studies definitely showed that, while the effect of *macroturbulence* in OB dwarfs is usually negligible when compared to rotational broadening, the effect of this extra-broadening is clearly present in OB Sgs.

Despite it was named *macroturbulence* at some point, the interpretation of this extra-broadening as the effect of

turbulent motions is quite improbable. The effect is present in photospheric lines and affects the whole profile, even the wavelengths close to the continuum. Therefore, whatever is producing the extra-broadening has to be deeply rooted in the stellar photosphere (and maybe below), in layers in which we do not expect any significant velocity field in these stars. If interpreted as turbulent motions, *macroturbulence* would represent *highly supersonic* velocities in many cases (Dufton et al. 2006; Lefever et al. 2007; Markova et al. 2008; Fraser et al. 2010). This interpretation is incompatible with the previous statement.

One physical mechanism suggested to be the origin of this extra-broadening relates to oscillations. Many OB Sgs are known to show photometric and spectroscopic variability. Based on this, Lucy (1976) postulated that this variability may be a pulsation phenomenon, and *macroturbulence* may be identified with the surface motions generated by the superposition of numerous nonradial oscillations. More recently, Aerts et al. (2009) computed time-series of line profiles for evolved massive stars broadened by rotation and thousands of low amplitude nonradial gravity mode oscillations and showed that the resulting profiles could mimic the observed ones. Stellar oscillations are therefore a plausible explanation for the extra-broadening in O and B Sgs, but so far there is no direct evidence confirming their presence.

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

** Corresponding author: e-mail: ssimon@iac.es

Table 1 List of observed stars, their spectral classification, V magnitude, $v \sin i$, *macroturbulence*, and peak-to-peak amplitude of the first and third moment from the Si III 4567 or O III 5592 lines. Note: $v \sin i$, Θ_G , and $\Delta < v >$ in km s^{-1} ; $\Delta < v^3 >$ in $\text{km}^3 \text{s}^{-3}$.

Star	Name	SpT & LC	V	$v \sin i$ (FT)		$Macrot.$	LPVs	
				Range	Median	Θ_G	$\Delta \langle v \rangle$	$\Delta \langle v^3 \rangle \times 10^5$
Early B-type Supergiants								
HD 209975	19 Cep	O9.5 Iab	5.11	54–61	57	65	10.1	0.99
HD 37128	ϵ Ori	B0 Ia	1.70	46–64	55	65	12.3	0.79
HD 38771	κ Ori	B0.5 Ia	2.05	46–57	51	55	9.4	0.49
HD 2905	κ Cas	BC0.7 Ia	4.18	44–59	52	60	10.1	0.63
HD 190603		B1.5 Ia ⁺	5.66	23–47	39	40	2.2	0.15
HD 14818	10 Per	B2 Ia 0	6.27	36–47	41	50	7.8	0.51
Dwarfs (Luminosity class V objects)								
HD 214680	10 Lac	O9 V	4.88	17–23	18	25	2.1	0.05
HD 37042	θ^2 Ori B	B0.5 V	6.02	32–34	33	<5	0.8	0.01

We present first results of an observational project aimed at investigating the extra line-broadening in O and B Sgs and its possible connection with spectroscopic variability phenomena and stellar oscillations.

2 The project

The observing campaigns for this project began already two years ago. We selected a sample of ~ 15 bright O and B stars, with the objective of obtaining time-series of high resolution, high signal-to-noise (SNR) spectra. With these time-series spectra we plan to (1) investigate and quantify the presence of line profile variations (LPVs); (2) investigate the origin of the LPVs, considering several possible physical explanations (not only stellar oscillations, but also wind variability in terms of density and/or velocity); (3) whenever possible, perform a seismic-like study, determining the frequencies associated with the LPVs and, subsequently, perform a mode identification and seismic modeling; (4) obtain the stellar and wind parameters of the selected stars through an spectroscopic analysis using the stellar atmosphere code FASTWIND (Puls et al. 2005); (5) characterize the line-broadening in photospheric lines by disentangling the projected rotational velocity ($v \sin i$) and the extra-broadening; (6) investigate the temporal behavior of these quantities; (7) look for empirical relations between the size of the extra-broadening, $v \sin i$, wind-variability, and the LPVs; (8) hopefully, obtain firm observational evidences about the physical origin of the extra-broadening.

Regarding point (3) above, this project will require an important amount of observational time (as it is usual in asteroseismic studies, e.g. Aerts et al. 2004; Handler et al. 2006; Uytterhoeven et al. 2008; Briquet et al. 2009; Poretti et al. 2009). Although we have already obtained time-series spectra during several observing campaigns (using FIES, SES, and HERMES spectrographs, attached to the NOT, STELLA and MERCATOR telescopes, respectively), the amount and time span of the collected spectra are still not enough for

a proper seismic study. New campaigns are planned to improve this situation. Meanwhile, the analysis of the available data sets are leading to interesting and motivating results. Here, we summarize the main results obtained from the analysis of the first campaign, with FIES.

3 First results from the FIES08 run

3.1 Selected targets and observational data set

In 2008 November, we obtained a first set of spectra with FIES@NOT in medium resolution mode ($R=46000$). During 4 nights we collected time-series of spectra for six OB Sgs. The sample was complemented with two OB dwarf stars, where the extra-broadening tends to be negligible with respect to the rotational broadening. The exposure times were chosen such as to reach at least a $\text{SNR}=200$ (measured in the range 4500–4600 Å). The list of observed stars, along with their spectral classification and V magnitude, is presented in Table 1.

3.2 Characterization of line-broadening in photospheric lines

We used the Fourier transform technique (Gray 1976; see also Simón-Díaz & Herrero, 2007 for a recent application to the spectra of O and B stars) to disentangle the rotational and *macroturbulent* broadening contributions. The results of the analysis are presented in Table 1. We performed the analysis for each of the time-series spectra, obtaining the $v \sin i$ indicated by the first zero of the Fourier transform. The range and median of derived $v \sin i$ values are indicated in the first and second columns of Table 1. Note that the dispersion in the obtained $v \sin i$ is between 10% and 30%, depending on the star. Whether this dispersion is real, or an effect of noise, is not clear from this data set. As outlined by Simón-Díaz & Herrero (2007), the correct identification of this zero is complicated in the cases of low SNR and a large

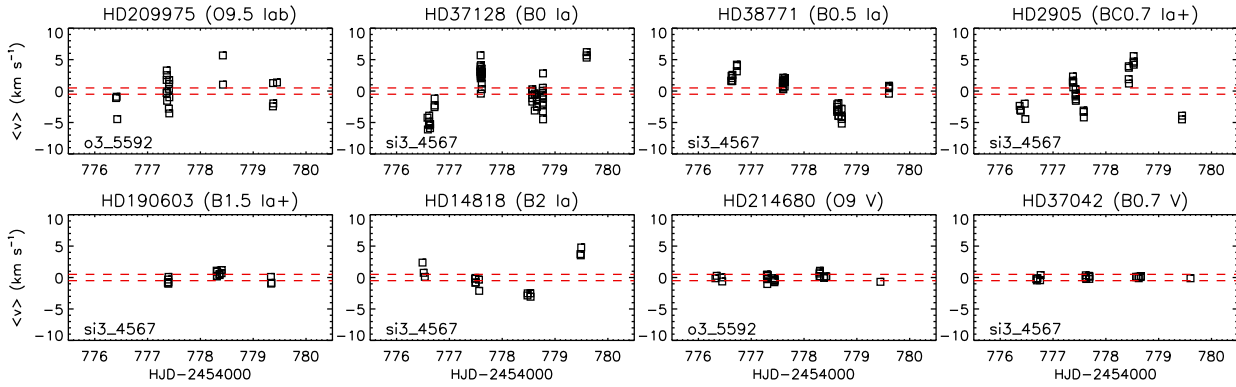


Fig. 1 Variation of the first moments (radial velocity placed at average zero) for the sample of stars derived from the Si III 4567 or O III 5592 line profiles. Horizontal lines show the accuracy associated with the instrumental setting used for FIES@NOT.

contribution of the extra-broadening. We plan to explore this in more detail in future.

Next, we considered the median $v \sin i$ values for each star and quantified the contribution of the extra-broadening by assuming a Gaussian-type profile. The corresponding values, indicated as Θ_G , are indicated in Table 1.

Note that the extra-broadening is significant in all the Sgs. This is not the case for the B0.5 V star HD 37042, where the total broadening is mainly produced by the effect of the stellar rotation. The other dwarf star, HD 214680 is a special case, since it has a very low $v \sin i$. For such a low $v \sin i$, microturbulence provides a significant contribution to the total broadening, which then is included in the measured extra-broadening.

3.3 Line profile variations in photospheric lines

Similarly to previous works studying spectroscopic variability in O and B Sgs (e.g. Ebbets 1982; Howarth et al. 1993; Fullerton, Gies, & Bolton 1996; Prinja et al. 1996, 2004, 2006; Morel et al. 2004; Kaufer et al. 2006; Markova et al. 2005, 2008), we found clear signatures of line profile variations (LPVs) for all the Sgs considered in our study. To quantitatively investigate these LPVs we computed the first, $\langle v \rangle$, and third, $\langle v^3 \rangle$, normalised velocity moments¹ from the Si III 4567 or O III 5592 lines². These moments are connected with the centroid velocity of the line and the skewness of the line profile, respectively.

Results for the first velocity moment³ are presented in Figure 1. The associated uncertainties (not included in the plot) are ~ 0.1 – 0.4 km s^{−1}. In the case of the dwarf star HD 37042, the $\langle v \rangle$ values are fairly constant. The maximum dispersion in velocity for this stars is ~ 1 km s^{−1}, of the order of the accuracy associated with the instrumental setting

¹ See definition in (Aerts et al. 2010).

² We used FAMIAS (Zima 2008), a software package developed in the framework of the FP6 European Coordination Action HELAS (<http://www.helas-eu.org/>).

³ The third velocity moment follows a similar temporal behavior.

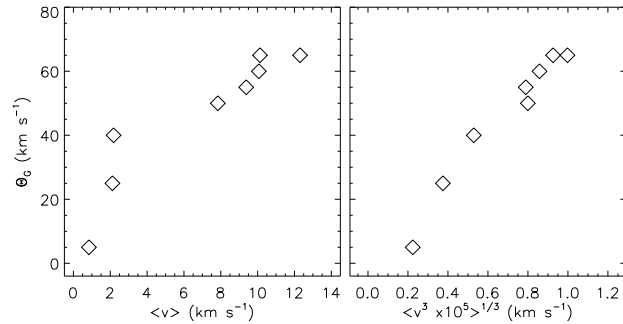


Fig. 2 *Macroturbulent* broadening (Θ_G) vs. peak-to-peak amplitude of the first and third moments of the line profile, for the sample from Table 1.

used for the FIES@NOT observations (indicated as red horizontal lines). All the other stars show $\langle v \rangle$ variations above this significance level, with maximum amplitudes ~ 10 – 12 km s^{−1}. The minimum variations are found for HD 190603 and HD 214680 (the other luminosity class V object considered in this study), with maximum amplitudes slightly larger than the significance level. We indicate in Table 1 the peak-to-peak amplitude of the first and third moment variations measured for each of the considered targets.

3.4 The *macroturbulence*-LPVs connection

We then investigated the possible connection between the *macroturbulent* broadening and the LPVs. Fig. 2 shows a clear positive correlation between the size of the *macroturbulent* broadening (Θ_G) and the peak-to-peak amplitude of variation of $\langle v \rangle$ and $\langle v^3 \rangle$. To our knowledge, this is the *first clear observational evidence ever presented for a connection between the extra-broadening and the LPVs in OB Sgs*. Particular remarkable is the Θ_G - $\langle v^3 \rangle$ correlation: the larger the extra-broadening, the more asymmetric line profiles can be found. Note that this does not mean that lines with an important *macroturbulence* contribution are always asymmetric since $\langle v^3 \rangle$ is oscillating between positive to negative values with time.

3.5 Frequency analysis

We searched for periodic signals in the spectral time-series of the best time-sampled candidates, and found indications for the presence of at least one long-term period of 0.5 to 3.5 days in the moment and pixel-to-pixel variations. This allows to discard phenomena connected to stellar rotation as the origin of the LPVs (rotational periods for these stars are of the order of several weeks to a few months). Unfortunately, the time span of our observations ($\Delta T=3.07$ d at best) is not long enough to permit a reliable frequency analysis, needed for a subsequent mode identification and seismic modeling. We hope to improve this situation with future observing runs.

4 Discussion

In the last decades, many studies have been performed which aimed at studying and providing empirical constraints on the different physical components that can yield temporal variability in the photospheric lines of luminous OB stars. It is quite common to find in them the suggestion that non-radial oscillations may be the origin of the LPVs, and the driver of large-scale wind structures. Observational evidence points towards this hypothesis, but a firm confirmation (by means of a rigorous seismic analysis) has not been achieved yet.

From a theoretical point of view, g-modes were not initially expected in B Sgs because the radiative damping in the core was suspected as too strong. Saio et al. (2006) claimed the detection of simultaneous p- and g-modes in HD 163899 (B2 Ib/II) using data from the MOST satellite. These authors also computed new models showing that g-modes can be excited in massive post-Main sequence stars, as the g-modes are reflected at the convective zone associated to the H-burning shell. Lefever et al. (2007) presented observational evidence of g-mode instabilities in a sample of photometrically variable B Sgs from the location of the stars in the ($\log g, \log T_{\text{eff}}$)-diagram. A similar conclusion can be achieved from the loci of our targets in this diagram.

It seems that macroturbulent broadening in OB Supergiants could be related to pulsations, but it is too premature to consider them as the only physical phenomenon to explain the unknown broadening. Nevertheless, our observational study clearly indicates a connection between *macroturbulence* and LPVs, whatever the origin of the latter.

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